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Abstract. The Liquid Argon Time Projection Chamber (LAr TPC) is a detection technique very well suited for the investigation of rare signals, including neutrino interactions. The ICARUS T600 is the largest LAr TPC ever built. It has recorded events both, from the CERN to Gran Sasso (CNGS) muon neutrino beam and cosmic rays interactions. Several important results have been achieved thanks to the three-dimensional event imaging and very good detector resolutions both, calorimetric and spatial. Two of them, namely the observation of a free electron lifetime exceeding 15 ms, and the search of LSND related anomalies in the ν_e appearance from the ν_μ CNGS beam will be shortly summarized.

1. The ICARUS T600 detector

Following C. Rubbia's idea of LAr TPC detection technique [1] the ICARUS Collaboration, finalized many years of *R&D* studies with a construction of the T600 detector which, with its 760 t of LAr (476 t active mass) represents the biggest LAr TPC built so far. The collection of both, the ionization electrons at anode wires, and scintillation light by photomultipliers (PMTs) allow to reconstruct, in three dimensions, any ionizing particles with spatial resolution of about 1 mm^3. The ICARUS T600 cryostat is split into two identical modules. Each of them houses two TPCs with a common cathode placed in the middle. The maximum drift length of electrons is equal to 1.5 m. The 500 V/cm uniform electric field drifts electrons with the drift velocity v_d = 1.6 mm/μs towards three anode wire planes (0°, ± 60° with respect to the horizontal direction), 3 mm apart. Thank to appropriate voltages, the signal is recorded in a non-destructive way in the first two *Induction* wire planes, whereas the ionization charge is collected on the last *Collection* plane. Arrays of PMTs, placed behind wire planes, detect prompt 128 nm scintillation light, providing the measurement of the absolute time T_0 of an ionizing event. Both, T_0 and v_d are used to determine the absolute position of the track along the drift coordinate. The ICARUS T600 detector is triggered mainly by the sum of PMTs signals. For CNGS beam events, the trigger is generated when the PMTs sum signal is present in at least one TPC chamber within 60 μs gate opened at the proton extraction time, which is known from the *Early Warning Signal* sent from CERN to LNGS 80 ms before each proton extraction. The coincidence of the PMTs sum signals in two adjacent chambers triggers cosmic ray events. Detailed description of the ICARUS T600 detector can be found in [2] and [3].

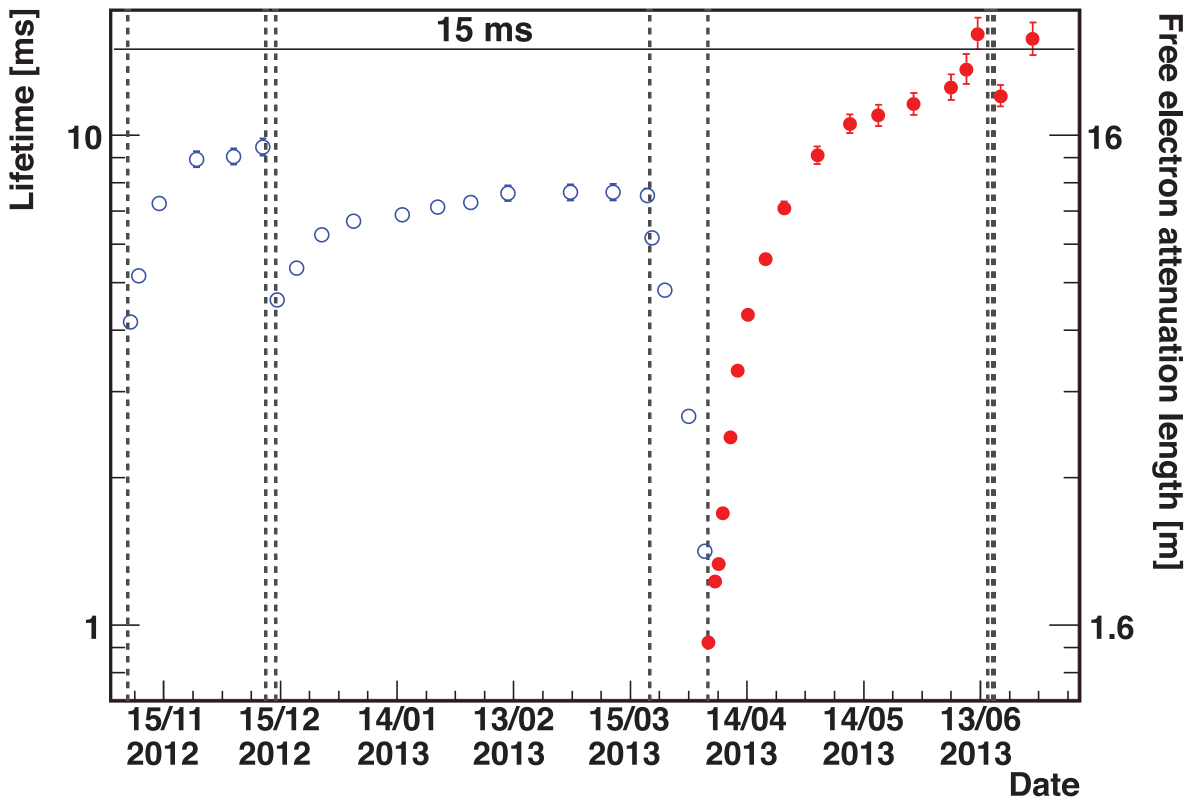

Figure 1. Electron lifetime and free electron attenuation length in the East module of the ICARUS T600 detector for the last period of data taking: full red points corresponds to the measurements with the new pump.

2. Electron lifetime and LAr purity

The operation of large LAr TPC requires to reach and maintain a very high level of LAr purity. Each ICARUS T600 module has been equipped with two gas Argon and one liquid Argon recirculation/purification systems ([3], [4]) which kept the electronegative impurities (mainly O_2, H_2O and CO_2) in LAr at a very low concentration level. The gas Argon, from the cryostat ceiling is continuously drawn, re-condensed, filtered and finally returned to the cryostat, whereas LAr is continuously recirculated by an immersed, cryogenic pumps (6 days for full volume recirculation) and finally re-injected into the cryostat. The attenuation of charge, produced by cosmic-ray muon tracks traversing the detector, was used to determine the electron lifetime. The results for the East cryostat are presented in Fig. 1. In April 2013 the ACD CRYO pump, used in the first two years of data taking, was replaced with a new Barber Nichols BNCP-32C-000 with an external motor. With the new pump, the electron lifetime started rising up, and reached $16.1^{+1.3}_{-1.1}$ ms before the detector stop. This electron lifetime corresponds to a maximum signal attenuation of 6% at the maximum drift distance of 1.5 m in the ICARUS T600 detector. The details of the electron lifetime determination in the ICARUS LAr TPC can be found in [5].

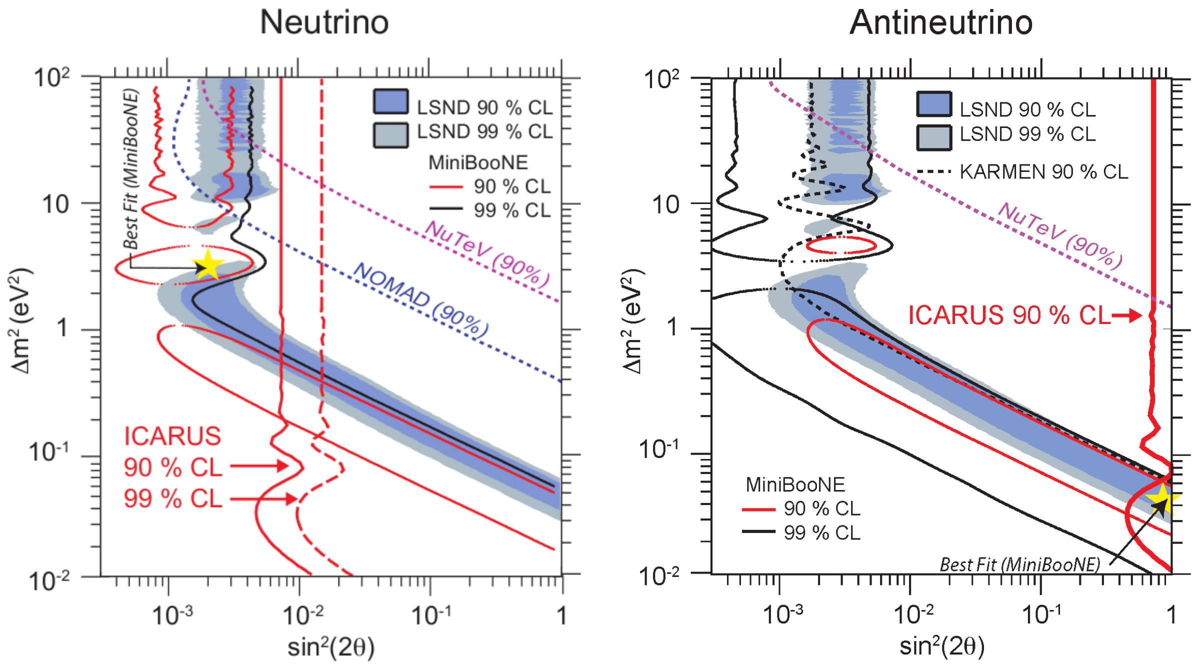

Figure 2. Δm^2 as a function of $\sin^2(2\theta)$ for neutrino (*left*) and antineutrino (*right*) for the main experiments sensitive to the $\bar{\nu}_\mu \to \bar{\nu}_e$ and $\nu_\mu \to \nu_e$ anomalies [6], [7], [8], [9] and [10]. The continuous red line represents ICARUS result, whereas the yellow stars mark the best fit points of MiniBooNE [7].

3. Search for anomalies in the electron neutrino appearance from a muon neutrino beam

The LSND experiment observed an excess of anti-ν_e neutrino events in anti-ν_μ beam: $87.9 \pm 22.4 \pm 6.0$ (3.8σ) [6], which was later partly confirmed by MiniBooNE collaboration [7]. These results may imply the existence of a new additional sterile neutrino flavors with the mass-squared difference Δm^2_{new} of about 0.01 to 1.0 eV^2 with a associated value of $\sin^2(2\theta_{new})$, which is highly incompatible with the three-neutrino mixing approach. Thanks to the excellent γ-electron separation in the LAr TPC, the ICARUS Collaboration searched for electron neutrino appearance in the CNGS ν_μ beam in the context of LSND-like anomalies. The first result, based on the study of 1955 neutrino events, corresponding to 6.0×10^{19} POT, was published in [11]. In this proceedings the updated analysis based on 2450 neutrino events, corresponding to the 7.2×10^{19} POT, described in details in [12], is summarized. Visual selection of electron neutrino event candidates in the detector fiducial volume, with an event energy less than 30 GeV (50% reduction of the beam ν_e background and only 15% reduction of the expected signal), was performed. The ν_e event signature required: (1) a single minimum ionizing particle (dE/dx $\leq$ 3.1 MeV/cm, excluding δ-rays) originating from the interaction vertex, over at least 8 wires long, later developing into an electromagnetic shower, and (2) minimum 150 mrad spatial separation from other tracks coming from the vertex at least in one of two transverse views. Taking into account the selection efficiency 0.74 ± 0.05, the expected number of ν_e events from known sources (residual ν_μ contamination in the ν_μ beam and events due to three neutrino mixing standard model predictions) is equal to 7.9 ± 1.0 (syst. error only). Six ν_e events have been found. This result is compatible with the expectations due to known sources, giving following limits (weighted for efficiency) on neutrino events due to LSND anomaly: 5.2 (90 % C.L.), or 10.3 (99 % C.L.), with corresponding limits on the oscillation probabilities: $P(\nu_\mu \to \nu_e) \leq 3.85$

$\times$ 10^{-3} (90 % C.L.) and P($\nu_\mu \rightarrow \nu_e$) $\leq$ 7.60 $\times$ 10^{-3} (90 % C.L.). The exclusion area of the ICARUS experiment is shown in Fig. 2. A 2% muon anti-neutrino contamination is present in the CNGS beam [13]. Assuming that the whole effect is due to $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$, the absence of an anomalous signal gives a limit of 4.2 events at 90% C.L., which corresponds to the limit on the oscillation probability P($\bar{\nu}_\mu \rightarrow \bar{\nu}_e$) $\leq$ 0.32, shown in Fig. 2 as the small exclusion area.

4. Conclusions

The ICARUS T600 detector had been acquiring data without interruption for more than 3 years, in the underground Gran Sasso laboratory, with both CNGS beam and cosmics, proving the maturity of this detection technique. Remarkable LAr purity had been achieved resulting in the electron lifetime of 16 ms, what is important for next generation experiments. Developed reconstruction algorithms allow to resolve most of the events collected, down to their single components. As an example, analysis of electron neutrino events has been shown. No evidence of oscillation into sterile neutrinos has been found. At the end of 2014 the ICARUS T600 detector has been transported to CERN for overhauling and refurbishment (upgrade of light collection system and electronics, new cold vessel, new passive insulation and new cathode) within the WA104 experiment (details can be found in [14]). The upgraded ICARUS T600, together with MicroBooNE and LAr1-ND detector comprises a combined Fermilab Neutrino program to address the short-baseline anomalies and search for sterile neutrinos.

5. Acknowledgements

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